Molecular emission lines in Herbig Ae/Be stars

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MOLECULAR EMISSION LINES IN HERBIG AeBe STARS

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ABSTRACT

We present the first ISO-LWS observations of the molecular FIR lines in 3 out of a sample of 11 Herbig Ae/Be stars (HAEBE), namely IRAS12496-7650, RCrA and LkHα234. High-J pure rotational CO lines (from $J_{up} = 14$ to $J_{up} = 19$) have been observed in all the spectra, while two (at 79 μm and 84 μm) and three OH lines (at 71, 79 and 84 μm) have been detected in LkHα234 and RCrA, respectively.
For all the sources the molecular emission has been consistently fitted with a Large Velocity Gradient (LVG) model and results as originated in a warm (T $\geq$ 200 K) and dense ($n_{H_2} \geq 10^5$ cm^{-3}) gas.
By comparing the observed cooling ratios with models predictions, we find that the FUV radiation is the most probable responsible for line excitation. Shock mechanism contributions can be reasonably ruled out, especially because of the absence in the spectra of any water vapour line, in contrast with the predictions on the molecular emission coming from warm shocked environments.

Key words: Stars: Circumstellar matter; Stars: Pre-Main Sequence (Ae/Be); Infrared: Lines; Infrared: Sources.

1. INTRODUCTION

The Herbig Ae/Be stars (HAEBE) are pre main-sequence stars considered as the higher mass counterpart of T Tauri stars. They represent an intermediate luminosity sample to be suitably targeted for statistical studies on the interactions with the parent cloud material which is still present in this evolutionary phase.
Molecular line observations are by far the most suitable probes to investigate the cooling and the kinematics of low temperature and high density gas. This latter, situated in the circumstellar (CS) neighbourhood, is exposed to the far-UV radiation from both the central exciting star and the interstellar field; moreover in many cases the interaction with the stellar wind results in gas heating by means of low and high velocity shocks (C/J-shocks). According to model predictions (e.g., Kaufman & Neufeld 1996), the molecular gas cooling is largely dominated by the high J-CO, H_2O, OH rotational transitions. These lines lie in a spectral range (50-200 μm) where only airplane observations have been so far carried out; however the demand of *safe* results prevented KAO (Kuiper Airborne Observatory) for investigating in details star formation regions different from the Orion nebula. Now the spectroscopic capabilities offered by ISO (Infrared Space Observatory), and in particular by the on board Long Wavelength Spectrometer (LWS), have allowed us to perform the first unbiased spectral survey in the FIR (45–197 μm) of a significant sample of HAEBE, thus giving us the opportunity of investigating from a statistical point of view the mechanisms at the origin of the molecular gas excitation.

2. OBSERVATIONS, DATA REDUCTION AND RESULTS

We have investigated a sample of 11 HAEBE stars as part of the guaranteed time programme observations

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carried out with the Long Wavelength Spectrometer (LWS: Clegg et al. 1996) on board the Infrared Space Observatory (ISO: Kessler et al. 1996). The results are reported and discussed in Lorenzetti et al. (1998, Paper I) and in Giannini et al. (1998, Paper II).
The spectra have been acquired with the LWS AOT01 full grating scan mode (i.e., 43-197 μm wavelength range, resolution R $\sim$ 200, instrumental beam size of $\sim$80 arcsec), using the 'fast scanning' option and a sampling of 1/4 of the spectral resolution element. The flux calibration has been derived on the basis of Uranus observations (accuracy of about 30%, Swinyard et al. 1996), while the uncertainty in wavelength calibration is about 25% of the resolution element (*i.e.* 0.07 μm and 0.15 μm for the short (43-90 μm) and the long (90-197 μm) wavelength ranges respectively). The preliminary analysis has been done with the off line pipeline version 7 (OLP-V7); the raw data have been successively processed with an internal pipeline for de-glitching from the spurious signals introduced by the impact of cosmic rays and for correcting the data from low-frequency fringes (Swinyard et al. 1996).
We revealed molecular emission in three objects, namely IRAS12496-7650, RCrA and LkHα234. For all these sources at least five transitions of the CO pure rotational lines (with J_{up} between 14 and 19) have been observed; in addition, we also observed in RCrA the OH $^2\Pi_{1/2,J=7/2}\rightarrow{}^2\Pi_{1/2,J=5/2}$, $^2\Pi_{1/2,J=1/2}\rightarrow{}^2\Pi_{3/2,J=3/2}$, $^2\Pi_{3/2,J=7/2}\rightarrow{}^2\Pi_{3/2,J=5/2}$ transitions at 71, 79 and 84 μm, respectively, while in LkHα234 only the 79 and 84 μm lines have been detected. The line fluxes were computed on the defringed single detector spectra by gaussian fitting the spectral profiles. Figures 1-3 show the continuum subtracted (by means of first or second order polynomial fitting) parts of the spectra where the molecular emission has been revealed.

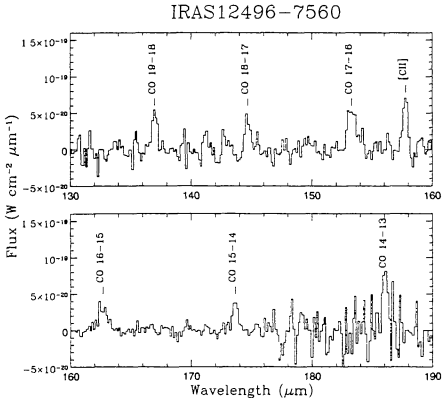

Figure 1. Portions of the LWS continuum subtracted spectra of IRAS 12496-7650 where the molecular emission has been detected.

3. LINE EMISSION FITTING

In order to understand the processes involved in the molecular emission, we have firstly derived the physical parameters of the emitting gas. To this aim, we solved the equations of statistical equilibrium for the

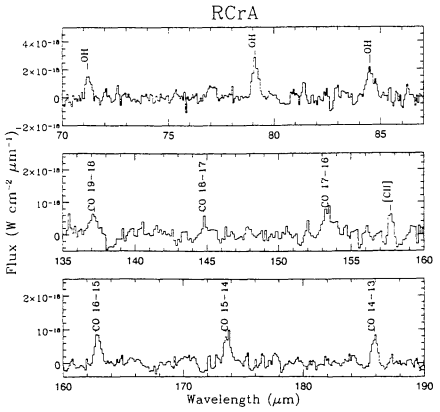

Figure 2. As in Figure 1, but for RCrA.

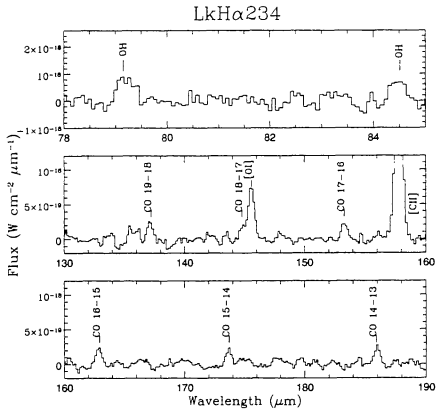

Figure 3. As in Figure 1, but for LkHα234.

level populations by adopting the standard approximation of a Large Velocity Gradient (LVG) regime in a plane-parallel geometry. The CO model takes into account the level populations of the first 60 rotational levels. The collisional downward rates by impacts of H_2 molecules for each couple of levels with $J_{up} \leq 60$ and $100 \leq T \leq 2000$ K are computed from the γ_{J0} coefficients, which represent the de-excitation rates from a level J to the ground level 0, taken from McKee et al. (1982). Upwards rates are computed using the principle of detailed balance. Radiative decay rates are taken from Chackerian & Tipping (1983). For the OH molecule model we consider the first 20 levels, accounting for the Λ doubling splitting, but disregarding the further splitting due to the hyperfine structure. The collisional downward rates are taken from Offer & van Dishoeck (1992), while the upward rates are computed with the same method as before. The radiative decays have been derived from the HITRAN catalogue (Rothman et al. 1987).
The model depends on a relatively large number of free-parameters: gas kinetic temperature, density, intrinsic linewidth, column density and filling-factor;

this circumstance, along with the relatively high uncertainties in the line flux determination, does not permit to uniquely define the physical conditions of the emitting gas. In principle, because we observe lines produced by two molecular species, we could independently model both the OH and the CO emission; unfortunately, the scarcity of the OH lines detected prevented a meaningful application of this procedure. So we preferred to fit the data using only the CO line fluxes, then checking the compatibility of the estimated gas temperature and density with the observed values derived from the OH line fluxes. In Table 1 all derived parameters are reported: the two values correspond to the extreme fits through the data; if both determinations are roughly coincident, a single value is given.

Table 1. Physical parameters of the molecular emission.

	IRAS 12496-7650	RCrA	LkHα234
T (K)	200 ÷ 750	300 ÷ 1000	200 ÷ 900
n_{H_2} (10^5 cm^{-3})	40÷ 5	40 ÷ 1.2	40 ÷ 5
Size (arcsec)	2.5	3.4 ÷ 10	2.5 ÷ 3.7
Size (10^{-3} pc)	2	2 ÷ 7	12 ÷ 18
N_{CO} (10^{17} cm^{-2})	24 ÷ 3	30 ÷ 4	10÷ 4
N_{OH} (10^{17} cm^{-2})	-	4	1.5÷ 4
L_{CO} (10^{-2} $L_\odot$)	0.3 ÷ 0.6	4	60 ÷ 100
L_{OH} (10^{-2} $L_\odot$)	-	8 ÷ 4	110 ÷ 75

4. EXCITATION MECHANISMS FOR THE MOLECULAR EMISSION

In all the three investigated sources both shock and quiescent excitation mechanisms have in principle to be taken into account as possibly responsible for the observed molecular emission. In fact all these sources have been recognized as drivers of CO molecular outflows and in some cases (RCrA and LkHα234) associated Herbig-Haro objects have also been discovered, thus revealing the presence of shock activity. However, contributions to the emission by photodissociation mechanism can not be excluded because of the presence of an enhanced UV field, as confirmed by the comparison between the FIR atomic lines and the current models of PDRs (see Paper I).

In particular, FIR molecular rotational transitions are expected to be the main gas coolants in the non-dissociative C-type shocks (e.g. Draine, Roberge, Dalgarno 1983, Kaufman & Neufeld 1990). These processes are characterized by having velocities usually lower than 40 kms^{-1} and temperatures not sufficiently high to dissociate the most abundant molecules, as H_2, CO, OH and H_2O.
Photodissociation regions occur where far-ultraviolet (FUV) radiation dominates the heating, so determining the chemical composition of the gas and its distribution with the distance from the central source. If the gas density is sufficiently high relatively to FUV flux (i.e. $n/G_o > 10^2$ cm^{-3}, being G_o measured in units of 1.6×10^{-3} ergs cm^{-2} s^{-1}, Habing 1968), the molecular self-shielding prevents the dissociation up

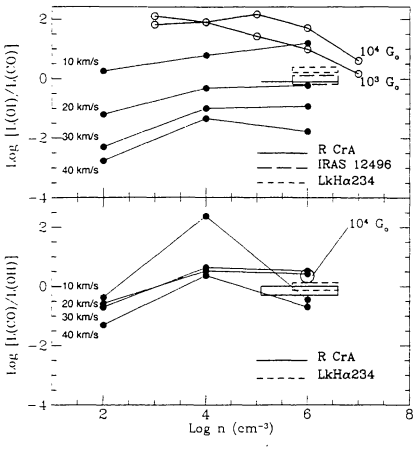

Figure 4. Cooling ratios of L(OI)/L(CO) (top panel) and L(CO)/L(OH) (bottom panel) vs. density. For the density range inferred from the LVG model, the fitted cooling ratios are superimposed to C-shock (filled circles) and to PDRs models (open circles). The horizontal and vertical bars indicate the possible ranges for density and molecular coolings, respectively. The same value for the pre-shock and post-shock density is assumed (see text).

to the surface of the molecular cloud (Burton, Hollenbach & Tielens 1990). In these 'clumpy' PDRs the contribution of the molecular lines to the total gas cooling becomes comparable or even greater than one of the atomic fine structure lines.
Molecular emission is predicted also by dissociative and high temperature J-type shocks with a relative cooling ratio with the ionic/atomic fine structure lines that depends on the pre-shock density conditions (e.g. Hollenbach & McKee 1989). In particular, for high density ($n \geq 10^5$ cm^{-3}) the FIR cooling is dominated by the H_2O rotational lines, while the CO rotational lines contribution is two order of magnitude lower. This circumstance is in contrast with our observations, so we can reasonably rule out the J-type shocks as excitation of the molecular line emission.
Aiming to test the remaining alternatives, we compared our observations with the C-shocks and dense PDRs model predictions. We plotted in Figure 4 the cooling ratios of [OI] 63 μm/CO (top panel) and CO/OH (bottom panel) derived from the LVG model as function of the local number density. These values are superimposed on the C-shocks predictions for different shock velocities of Draine, Roberge & Dalgarno (1983) (filled circles) and on the clumpy PDRs ones by Burton, Hollenbach & Tielens (1990) for different FUV radiation field (open circles).
Whereas PDR models and observed data are given as a function of the actual density, the C-shock models refer to *pre-shock* density. In this sense, the plot depicted in Figure 4 is fully consistent only if the pre-shock equals the post-shock density value. A more realistic case should be obtained by assuming a compression factor $n_{post-shock}/n_{pre-shock}$ between 10 and 100: accordingly the C-shock models would shift towards densities increased of the same factor, consequently reinforcing the agreement with the ob-

served data and suggesting the C-shock mechanism as possible responsible for the gas excitation. Nevertheless, in this picture some significant questions remain unresolved. Most importantly, all the C-type shocks models predict water vapour lines to be by far the dominant coolant of the gas, at least when the temperature reaches the threshold value of about 400 K, as suggested by our CO lines fits. In fact, at these temperatures, all the Oxygen not still locked into grains is converted through two subsequent chemical reactions, firstly into OH, and then, quite quickly, into water (Elitzur & de Jong 1973). As a consequence of these processes the H_2O abundance results rapidly increased, while the OH one is definitively reduced. In particular, for the derived ranges of densities and shock velocities, the smallest expected values of the ratios $L(H_2O)/L(OH)$ and $L(H_2O)/L(CO)$ are of the order of 10^2 and of 10 respectively, strongly in contrast with our observational findings. A C-shock interpretation would be still reconcilable with the data only in the quite unlike scenario where the three sources have been all observed during the same very short time phase (about 100 yr long) in which the OH molecule is not yet converted into water (Bergin, Melnick & Neufeld 1997).

On the contrary, the clumpy PDRs model seems to provide the only explanation for what we observe (Paper I/II). In fact, the absence of water lines is fully explained: despite on the self-shielding, the dissociation of the H_2O molecule into OH + H can not be prevented except deeply inside the cloud. On the contrary, the OH can more easily survive, being its photodissociation cross section at the Lyα wavelength an order of magnitude lower than that of H_2O (van Dishoeck & Dalgarno 1984).
Moreover, for the estimated temperatures and densities, the 'clumpy' PDR model predicts roughly the following abundance ratios: $X(CO)/X(H_2O)\sim50$, $X(OH)/X(H_2O)\sim15$, $X(CO)/X(OH)\sim3$. The first two ratios cannot be quantitatively checked through the data because, due the ISO-LWS sensitivity, they are beyond the detection limit, but well compatible with it. The third ratio, that relates species directly observed, can be inferred from observations, and our derived value is just ~ 4 for both RCrA and LkHα234.

Summarizing, we can conclude that strong indications supporting a PDR dominating mechanism are deduced from the observations. Contributions to the emission from C-shocks can not be definitively excluded, at least for the IRAS12496-7650 source, in which only the CO emission is detected and then no molecular cooling ratio can be derived.

5. CONCLUSIONS

The main conclusions from this work can be summarized as follows:

- ISO-LWS observations allowed the first detections of FIR molecular lines for three HAEBE stars (IRAS12496-7650, RCrA and LkHα234) out of a sample of 11 objects.
- High J-CO pure rotational lines (from J_{up} = 14 to J_{up} = 19) have been detected in all the sources; some OH lines are present in RCrA and LkHα234 spectra, while no evidence of water vapour emission has been revealed.
- The data have been consistently fitted with an LVG model. For all the objects the emission results originated by a warm and dense gas, located in very compact regions.
- Whereas the OH lines are detected, the correspondent estimated abundances are always greater of about two order of magnitude with respect of the common values of the interstellar medium.
- Photodominated mechanisms as expected in high density or clumpy environments, are likely responsible for the emission, while shocks can be reasonably ruled out. These findings are supported by the simultaneously absence of water vapour lines and overabundance of OH, circumstances which can be explained only in photodominated environments.

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